Automatic Generation Control of Two-area Interconnected Hydro-Hydro Restructured Power System with TCPS and SMES

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***Abstract*—Non-minimum phase characteristic of hydro turbine shows an opposite initial power surge in the event of frequency disturbance, thus possesses widely different characteristic than thermal generating unit. This paper presents Automatic Generation Control (AGC) of an interconnected two-area multiple-units hydro-hydro power system in restructured electricity market. The step load perturbation to such a system results in heavy frequency oscillations and the system is unable to regain its stable state as the positive real parts of some eigenvalue pairs confirm the inherent dynamically unstable characteristic of the system. To stabilize the frequency oscillations, impacts of Superconducting Magnetic Energy Storage (SMES) placed at terminal of area and Thyristor Controlled Phase Shifter (TCPS) located in series with tie-line have been investigated. Two cases such as (a) SMES-SMES coordination and (b) TCPS-SMES coordination are evaluated to compare their effectiveness to suppress the frequency oscillations. The parameters of TCPS, SMES and integral gains of AGC loop are optimized through craziness-based particle swarm optimization algorithm in order to have the optimal transient response of the system under different PoolCo and bilateral transaction in restructured electricity market.**

***Index Terms*—AGC, Deregulation, SMES, TCPS**

I. Introduction

Automatic generation control has been used for several years to meet the objective of maintaining the system frequency at nominal value and the net tie line power interchange from different areas at their scheduled values. The concept of conventional AGC is discussed in [1]–[3]. Controlling the frequency has always been a major subject in electrical power system operation and is becoming much more significant recently with increasing size, changing structure and complexity in interconnected power systems. In a competitive electricity market, there will be many market players, such as generating companies (Gencos), distribution companies (Discos), transmission company (Transco), and system operator (SO). For stable and secure operation of a power system, the SO has to provide a number of ancillary services. One of the ancillary services is the "frequency regulation" based on the concept of the load frequency control. A detailed discussion on load frequency control issues in power system operation after deregulation is reported in [4]-[8]. The AGC in a restructured electricity market should be designed to consider different types of possible transactions such as PoolCo-based transactions, bilateral transactions, and a combination of these two [7]. In this new paradigm, a Disco can contract individually with a GENCO for power and these transactions are done under the supervision of the System Operator (SO). Hence, situations may arise where DISCO make contract with only hydro generating units in competitive market place. In this paper we have analyzed the issue of AGC in restructured power system where contracts of DISOC exist only with GENCO based on hydro generating units.

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II. Linearized model of an interconnected two-area multi units hydro-hydro power system

Fig. 1 shows the schematic of an interconnected two-area power system. Each area has two GENCOs based on hydro generation and two DISCOs. Let GENCO1, GENCO2, DISCO1, and DISCO2 be in area I and GENCO3, GENCO4, DISCO3, and DISCO4 be in area II. Fig. 2 shows a complete block diagram of an interconnected two-area multi-units all-hydro power system for AGC study. The nominal system parameters are given in appendix [9]. The closed loop system in Fig. 2 is characterized in state space form as

$$\dot{x} = A^{cl}x + B^{cl}u$$

where x is the state vector and u is the vector of power demands. State matrix A^{cl} is constructed from Fig. 2 and given in appendix. Eigenvalue analysis of the state matrix A^{cl} for a given operating conditions shows the positive real parts for some eigenvalue pairs (shown as shaded in Table 1) which indicate that the system itself is inherently unstable. Thus, load frequency stabilization can never be possible for such an all-hydro test system after the load perturbation.

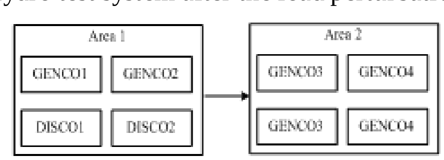

Figure 1. Schematic of two-area system in restructured power system

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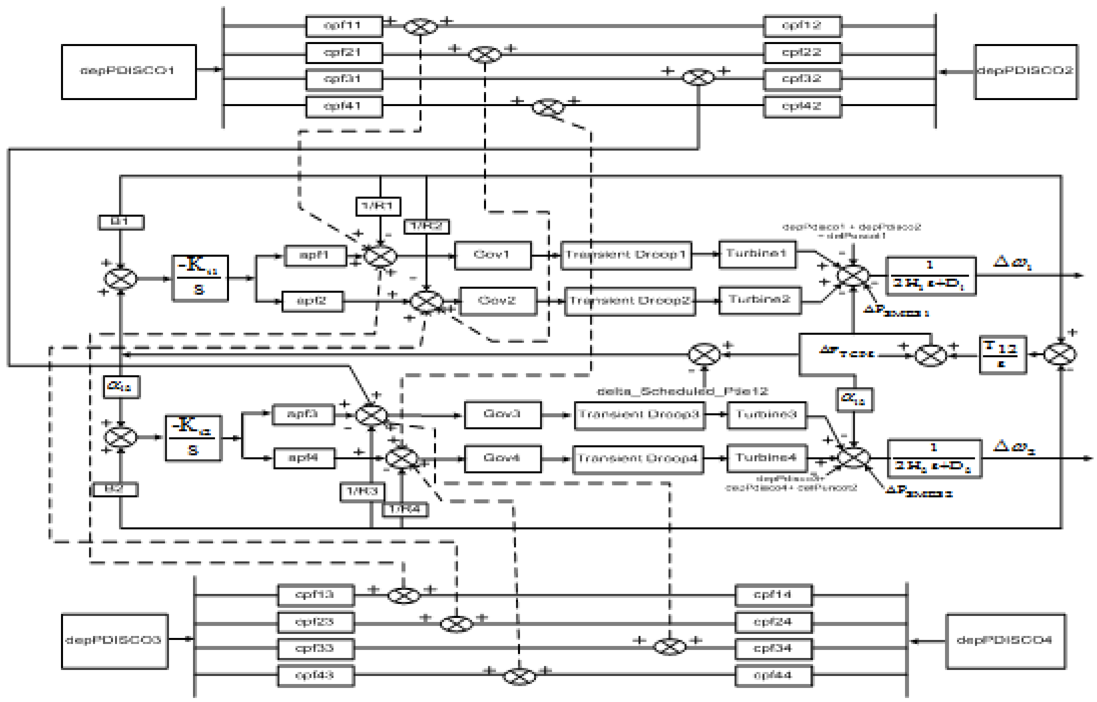

Figure 2. Linearized model of an interconnected two-area restructured power system

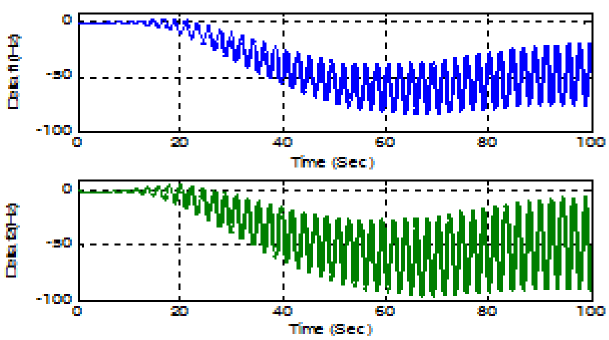

Figure 3. Area frequency response of system after 10% step load

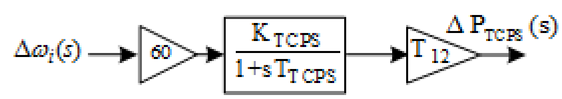

Figure 4. Structure of TCPS as frequency stabilizer

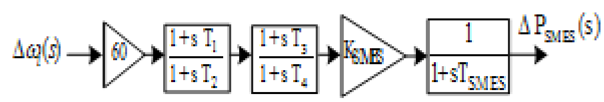

Figure 4. Structure of SMES as frequency stabilizer

TABLE I

EIGENVALUE ANALYSIS OF TEST SYSTEM

-6.9793	-6.9782	-5	-5
0.04+1.1i	0.041-1.1i	0.024+1.08i	0.024-1.08i
-2	-2	-0.2485	-0.2083
-0.0127	-0.0537	-0.0352	-0.0261
-0.0261			

Fig. 3 shows the transient response of the system after 10% step load perturbation in area 1. It has been observed that under the occurrence of load changes, a system frequency is heavily perturbed from its normal operating point and system does not regain its stable state. To overcome this inherently unstable situation and to make the system stable against any load disturbance, the impact of Thyristor Controlled Phase Shifter (TCPS) [10] and Superconducting Magnetic Energy Storage (SMES) [11] are analyzed. The structure of TCPS and SMES as frequency stabilizers are shown in Figs. 4 and 5 respectively. TCPS is located in series with tie-line near area 1whereas SMES is placed at the terminal of area(s).

III. MATHEMATICAL PROBLEM FORMULATION

The objectives of AGC are to reestablish primary frequency regulation, restore the frequency to its nominal value as quickly as possible and minimize the tie-line power flow oscillations between neighboring control areas. In order to satisfy the above requirements, gains (K_{I1}, K_{I2}) of integral controller in AGC loop, parameters of TCPS (K_{TCPS}, T_{TCPS}) and the parameters of SMES $(K_{SMES}, T_{SMES}, T_1, T_2, T_3 \text{ and } T_4)$) are to be optimized. In the present work, an Integral Square Error (ISE) criterion is used to minimize the objective function defined as:

$$\text{Figure of Demerit(FDM)} = \sum \left[\Delta f_1^2 + \Delta f_2^2 + \Delta P_{tie}^2 \right] \Delta T \qquad (1)$$

where ΔT = a given time interval for taking samples, Δf = incremental change in frequency and ΔP_{tie} = incremental change in tie-line power. The objective function is minimized with the help CRPSO based optimization techniques.

IV. CRAZINESS BASED PARTICLE SWARM OPTIMIZATION

The PSO was first introduced by Kennedy and Eberhart [12]. It is an evolutionary computational model, a stochastic

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search technique based on swarm intelligence.
Velocity updating equation:

$$v_i^{k+1} = v_i^k + c1 \times r1 \times \left(\text{pBest}_i - x_i^k\right) + c2 \times r2 \times \left(\text{gBest} - x_i^k\right)$$
(2)

Position updating equation:

$$x_i^{k+1} = x_i^k + v_i^{k+1} \quad (3)$$

The following modifications in velocity help to enhance the global search ability of PSO algorithm as observed in CRPSO [13].

(i) Velocity updating as proposed in [13] may be stated as in the following equation:

$$v_i^{k+1} = r2 \times v_i^k + (1-r2) \times c1 \times r1 \times \left(\text{pBest}_i - x_i^k\right) + (1-r2) \times c2 \times (1-r1) \times \left(\text{gBest} - x_i^k\right) \quad (4)$$

Local and global searches are balanced by random number r2 as stated in (5). Change in the direction in velocity may be modeled as given in the following equation:

$$v_i^{k+1} = r2 \times \text{sign(r3)} \times v_i^k + (1-r2) \times c1 \times r1 \times \left(\text{pBest}_i - x_i^k\right) + (1-r2) \times c2 \times (1-r1) \times \left(\text{gBest} - x_i^k\right) \quad (5)$$

In (5), sign (r3) may be defined as

$$\text{sign}(r3) = \begin{cases} -1 & (r3 \le 0.05) \\ 1 & (r3 > 0.05) \end{cases}$$

(ii) Inclusion of craziness: Diversity in the direction of birds flocking or fish schooling may be handled in traditional PSO with a predefined craziness probability. The particles may be crazed in accordance with the following equation before updating its position.

$$v_i^{k+1} = v_i^{k+1} + Pr(r4) \times sign(r4) \times v_i^{\text{craziness}} \quad (6)$$

where, Pr(r4) and sign(r4) are defined respectively as:

$$Pr(r4) = \begin{cases} 1 & (r4 \le P_{\text{craz}}) \\ 0 & (r4 > P_{\text{craz}}) \end{cases} \quad (7)$$

$$\text{sign}(r4) = \begin{cases} 1 & (r4 \ge 0.5) \\ -1 & (r4 < 0.5) \end{cases} \quad (8)$$

During the simulation of PSO, certain parameters require proper selection, as PSO is much sensitive to the selection of input parameters. The best chosen maximum population size = 50, maximum allowed iteration cycles = 100, best Pcraz = 0.2 (chosen after several experiments), best values of c1 and c2 are 1.65. The choice of c1, c2 are very much vulnerable for PSO execution. The value of $v_i^{\text{craziness}}$ lies between 0.25 and 0.35. The novelty of CRPSO lies with the fact of its faster convergence to the true optimal solution as compared to its other counter parts.

V. Simulation Results And Discussion

The concept of a "DISCO participation matrix" (DPM) is used to make the easier visualization of contracts between GENCOs and DISCOs [7]-[8]. Each area is having two GENCOs and two DISCOs. Let GENCO1, GENCO2, DISCO1 and DISCO2 be in area1 and GENCO3, GENCO4, DISCO3 and DISCO4 be in area2. Unlike in the traditional AGC system, a DISCO asks/demands a *particular* GENCO or GENCOs for load power. Thus, as a particular set of GENCOs are supposed to follow the load demanded by a DISCO, information signals must flow from a DISCO to a particular GENCO specifying corresponding demands.

The demands are specified by cpf_s (elements of DPM) and the pu MW load of a DISCO. These signals which were absent in traditional AGC will carry information as to which GENCO has to follow a load demanded by which DISCO. $apf_i\,(i = 1,2,3,4)$ are the Area Control Error (ACE) participation factors of different GENCOS.

$$\text{DPM} = \begin{bmatrix} cpf11 & cpf12 & cpf13 & cpf14 \\ cpf21 & cpf22 & cpf23 & cpf24 \\ cpf31 & cpf32 & cpf33 & cpf34 \\ cpf41 & cpf42 & cpf43 & cpf44 \end{bmatrix} \quad (9)$$

For TCPS-SMES coordination, TCPS is considered in series with a tie-line near area 1 and SMES is placed at the terminal of area2 whereas for SMES-SMES coordination, SMES units are considered at the terminal of both areas.

Case 1: PoolCo based transaction:

An event is simulated in which a system shown in Fig. 2 is subjected to step load perturbations as given in (10) [7]-[8] at t = 5 sec.

The GENCOs in each area participate equally in AGC, indicated by Area Control Error (ACE) participation factors $apf_i\,(i = 1,2,3,4)$.

$$\text{DPM} = \begin{bmatrix} 0.5 & 0.5 & 0.0 & 0.0 \\ 0.5 & 0.5 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.5 & 0.5 \\ 0.0 & 0.0 & 0.5 & 0.5 \end{bmatrix}; \begin{bmatrix} \Delta P_{L1} \\ \Delta P_{L2} \\ \Delta P_{L3} \\ \Delta P_{L4} \end{bmatrix} = \begin{bmatrix} 0.05 \\ 0.05 \\ 0.05 \\ 0.05 \end{bmatrix}; \begin{bmatrix} \Delta P_{L,\text{uncot1}} \\ \Delta P_{L,\text{uncot2}} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \quad (10)$$

$$apf_1 = 0.5, apf_2 = 0.5, apf_3 = 0.5, apf_4 = 0.5$$

The 0.05 pu load is demanded by DISCO1 and DISCO2 identically from their local GENCOs in area1 only, i.e. GENCO1 and GENCO2, which is indicated by each non-zero participation factor of 0.5 in DPM. Similarly, DISCO3 and DISCO4 demand 0.05 pu load from their local GENCOs in area 2, i.e. GENCO3 and GENCO4. As there is no contracts between inter-area GENCOs-DISCOs, the inter-area participation factors of DPM (shown shaded in (10)) are zero. This type of overall transaction is called as PoolCo transaction. The uncontracted load demand $\Delta P_{L,\text{uncot1}}$ and $\Delta P_{L,\text{uncot2}}$ of the area1 and area2 respectively are zero. The transient response of the system for the transaction given by (10) is shown in Fig. 6. It is clearly observed that the coordination of SMES-SMES and TCPS-SMES effectively suppress the area frequency and tie-line power oscillations and stabilize the system effectively. The optimized parameters for both coordinated system are

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given in Table II. Power generation response shown in Fig. 6 indicates that the initial surge of power is in the opposite direction to that desired due to non-minimum phase characteristic of hydro turbine [9]. Hence, issue of LFC with only hydro generating unit has become very critical and needs a special coordinated control of TCPS-SMES or SMES-SMES. Since there are no contracts of power between a GENCO in one area to a DISCO in another area, the scheduled steady state power flow over the tie line is zero.

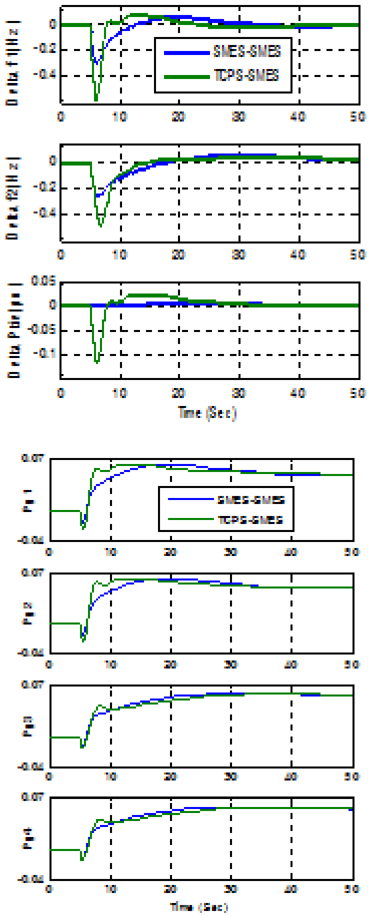

Figure 5. Case 1

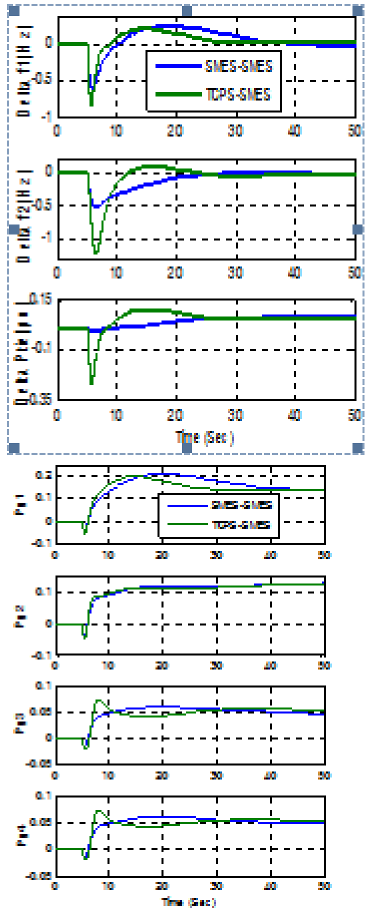

Figure 6. Case 2

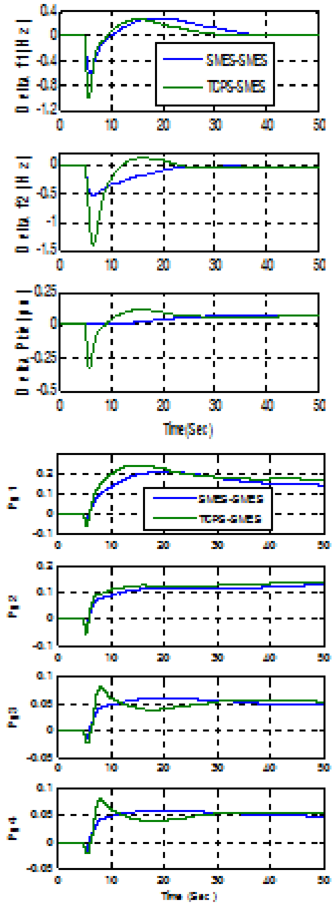

Figure 7. Case 3

Case 2: Bilateral Contracts:

The nonzero participation factor of DPM of (11) represents both PoolCo and bilateral types of transactions unlike that indicated by DPM of (10). The apf_1 of GENCO1 is the highest; the apf_2 of GENCO2 is the lowest which indicates that the participations of GENCO1 and GENCO2 in zeroing ACE are the highest and the lowest respectively. The total generation required of individual GENCOs can be calculated as [8]:

$$DPM = \begin{bmatrix} 0.45 & 0.45 & 0.30 & 0.35 \\ 0.45 & 0.45 & 0.30 & 0.35 \\ 0.05 & 0.05 & 0.20 & 0.15 \\ 0.05 & 0.05 & 0.20 & 0.15 \end{bmatrix} ; \begin{bmatrix} \Delta P_{L1} \\ \Delta P_{L2} \\ \Delta P_{L3} \\ \Delta P_{L4} \end{bmatrix} ; \begin{bmatrix} 0.15 \\ 0.05 \\ 0.05 \\ 0.15 \end{bmatrix} ; \begin{bmatrix} \Delta P_{L,uncot1} \\ \Delta P_{L,uncot2} \end{bmatrix} ; \begin{bmatrix} 0.0 \\ 0.0 \end{bmatrix} \tag{11}$$

$$apf1 = 0.75, apf2 = 0.25, apf3 = 0.5, apf4 = 0.5$$

$$\Delta P_G\_matrix = cpf\_matrix * \Delta P_L\_matrix' + apf\_matrix * \Delta P_{L,uncot}' \tag{12}$$

The mutual scheduled tie-line power flows among the areas can be represented as [8]:

$$Scheduled\_P_{tie,1-2} = \left(\left(cpf_{13}\Delta P_{L3} + cpf_{14}\Delta P_{L4} + cpf_{23}\Delta P_{L3} + cpf_{24}\Delta P_{L4} \right) / \alpha_{12} \right) - \left(cpf_{31}\Delta P_{L1} + cpf_{32}\Delta P_{L2} + cpf_{41}\Delta P_{L1} + cpf_{42}\Delta P_{L2} \right) \tag{13}$$

The dynamic responses for combined PoolCo and bilateral transactions are shown in Fig. 7. In this case also, the coordination of SMES-SMES and TCPS-SMES

TABLE II
OPTIMIZED PARAMETERS OBTAINED BY CRPSO FOR TCPS-SMES AND SMES-SMES COORDINATION

SMES-SMES Coordination						
Area 1						
K_{smes1}	T_{smes1}	T_1	T_2	T_3	T_4	K_{i1}
0.30	0.04	0.12	0.03	0.56	0.3	-0.4
Area 2						
K_{smes2}	T_{smes2}	T_1	T_2	T_3	T_4	K_{i2}
0.30	0.04	0.30	0.02	0.65	0.3	-0.13
TCPS-SMES Coordination						
Area 1						
K_{TCPS}	T_{TCPS}	K_{i1}				
0.4	0.091	-0.4				
Area 2						
K_{smes2}	T_{smes2}	T_1	T_2	T_3	T_4	K_{i2}
0.30	0.04	0.30	0.025	0.8	0.22	-0.1

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works satisfactorily. As the inter-area bilateral contacts exist between the DISCOs and GENCOs, scheduled tie-line power are observed on the tie-line in steady state also.

Case 3: Contract violation

It may happen that a DISCO violates a contract by demanding more power than that specified in the contract. This excess power is not contracted out to any GENCO. This un-contracted power must be supplied by the GENCOs in the same area as the DISCO. It must be reflected as a local load of the area but not as the contract demand. Consider case 2 again with a modification that DISCO demands 0.05 pu MW of un-contracted excess power in (11) i.e. $\Delta P_{L,un\cot 1} = 0.05\text{pu}$. Fig. 8 shows the stabilized transient response in the event of contract violation with the coordinated device operations.

The convergence characteristic of the objective function given in (1) with the help of CRPSO algorithm is shown in Fig. 9.

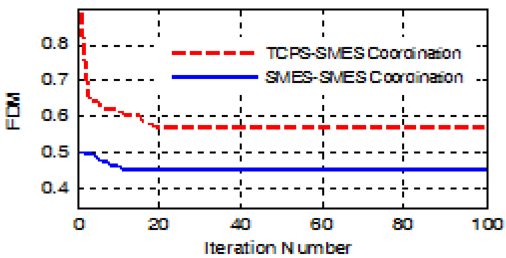

Figure 8. Convergence characteristic obtained by CRPSO for TCPS-SMES and SMES-SMES coordination

VI. Conclusion

Eigenvalue analysis of an interconnected two area multiple unit hydro-hydro power system results in positive real parts for some of the eigenvalue pairs which confirms its dynamically unstable behavior. The optimized coordination of SMES-SMES and TCPS-SMES with the help of CRPSO effectively stabilize the system and significantly improves the transient response of area frequency and tie-line power exchanges under different contract variation in restructured electricity market. The performance of SMES-SMES coordination yields the least value of *Figure of Demerit* and shows lesser undershoot and overshoot in dynamic responses of frequency and tie-line power exchanges as compared to TCPS-SMES coordination.

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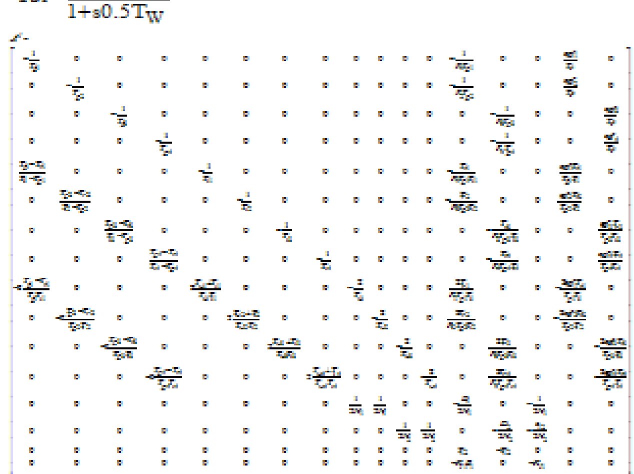
Appendix

$R=0.05, H=3s, D=1; \alpha_{12}=-1; T_G=0.2s; T_R=5s; T_W=1s; R_T=0.38;$

$B=21; T_{12}=0.5; Gov=\dfrac{1}{1+sT_G}; \text{Transient droop}=\dfrac{1+sT_R}{1+s(R_T/R)T_R};$

$Tur=\dfrac{1-sT_W}{1+s0.5T_W}$



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